$$n \rightarrow p + e^- + \bar{\nu}_e$$

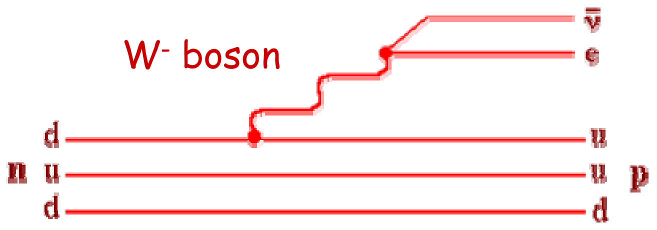
- a fundamental Weak Interaction process
- lifetime τ is relatively long: $\tau \sim \dfrac{1}{\lambda}$, $\lambda \sim \left[\int \psi_f^* \, V(r) \, \psi_i \; d^3 r \right]^2$ *(lecture 6!)*

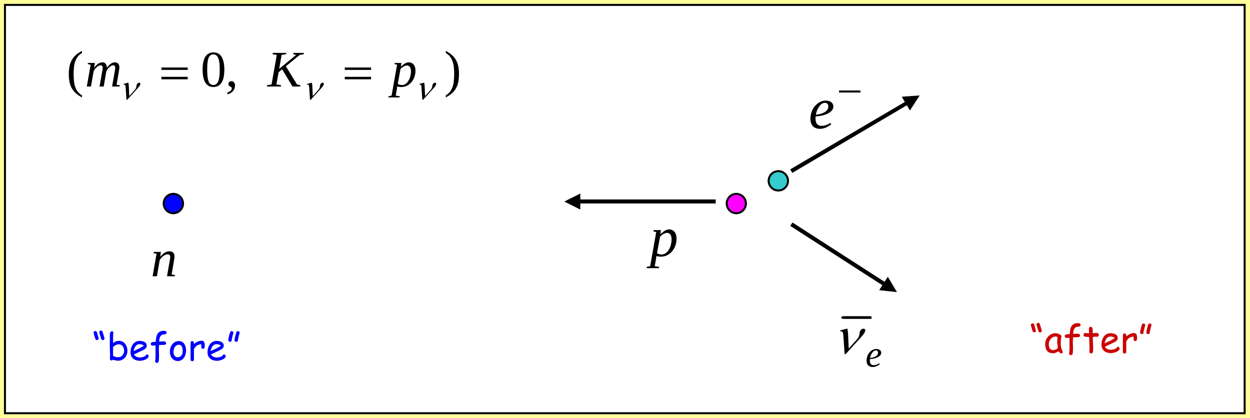
  large τ implies small transition rate λ, therefore 'weak' interaction V(r)

  compare to Δ resonance decay: $\Delta^+ \rightarrow p + \pi^0$, a strong interaction process, with τ = 5.7 x 10^{-24} seconds!!!

- precision studies of neutron decay are a very important testing ground for the "Standard Model" of fundamental interactions, as we shall see....
- interaction is almost pointlike, that is, the neutron disappears and the decay products appear almost instantaneously at the same place. (Fermi theory)
- modern picture:

(M_W = 80 GeV; R~ 0.002 fm)





1) $m_n = m_p + m_e + K_p + K_e + K_\nu$ (energy cons.)

2) $\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0$ (momentum)

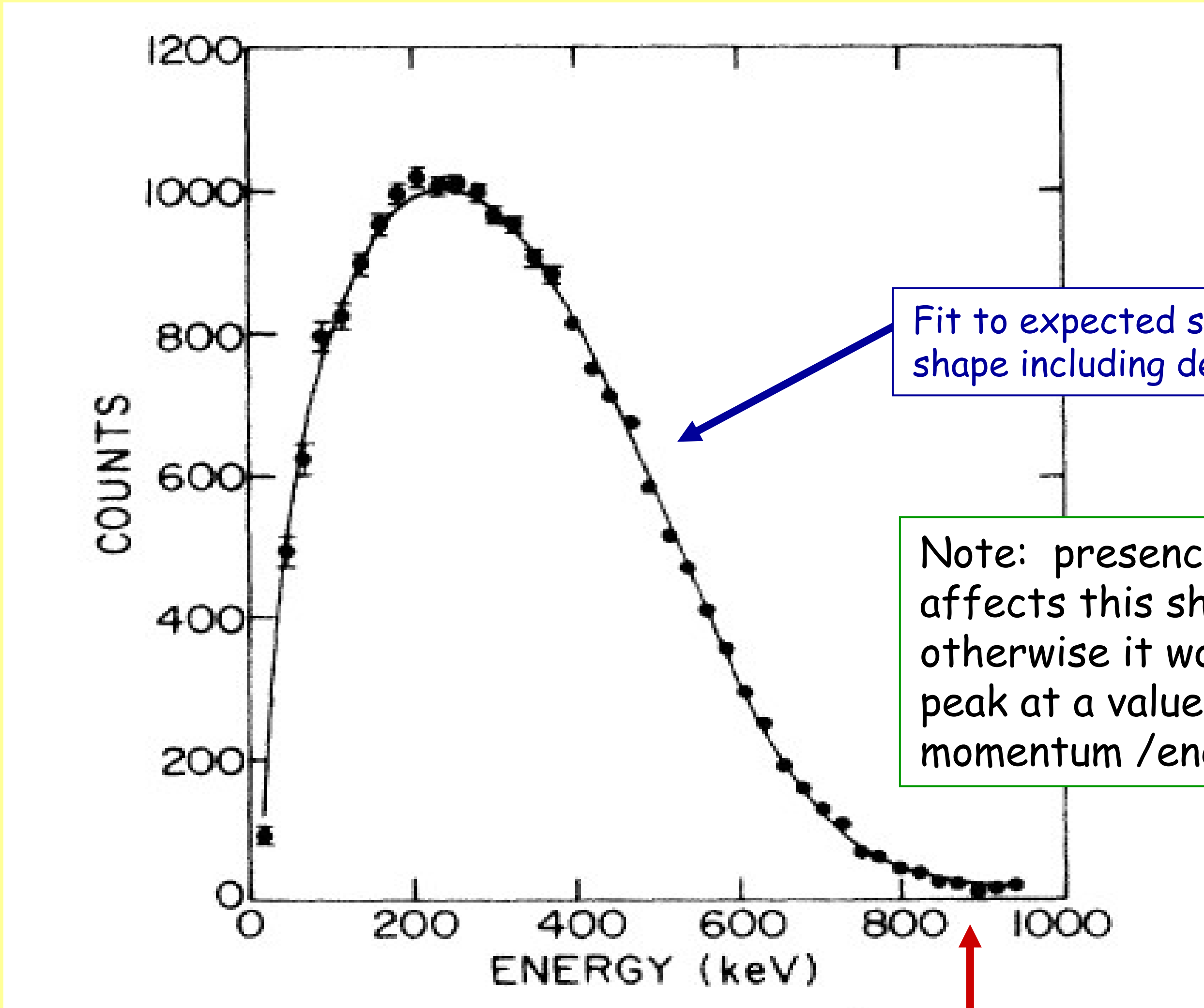
Define the "Q – value": (in general, Q > 0 for a reaction to proceed)

$$\boxed{Q \equiv m_n - m_p - m_e = K_p + K_e + K_\nu}$$

From Particle Data Group entries: Q = 0.78233 ± 0.00006 MeV (± 60 eV!)

Electron Energy Spectrum from “PERKEO” expt. at ILL reactor, France:

Bopp et al., Phys. Rev. Lett. 56, 919 (1986)



Fit to expected spectrum shape including detector model.

Note: presence of neutrino affects this shape dramatically – otherwise it would be a sharp peak at a value determined by momentum /energy conservation!

Endpoint smeared with detector resolution

Case study: "state of the art" neutron lifetime measurement

PHYSICAL REVIEW C **71**, 055502 (2005)

Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam

J. S. Nico, M. S. Dewey, and D. M. Gilliam
National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

F. E. Wietfeldt
Tulane University, New Orleans, Louisiana 70118, USA

X. Fei and W. M. Snow
Indiana University and Indiana University Cyclotron Facility, Bloomington, Indiana 47408, USA

G. L. Greene
University of Tennessee/Oak Ridge National Laboratory, Knoxville, Tennessee 37996, USA

J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel
European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, B-2440 Geel, Belgium

R. D. Scott
Scottish Universities Research and Reactor Centre, East Kilbride G75 0QU, United Kingdom
(Received 16 November 2004; published 25 May 2005)

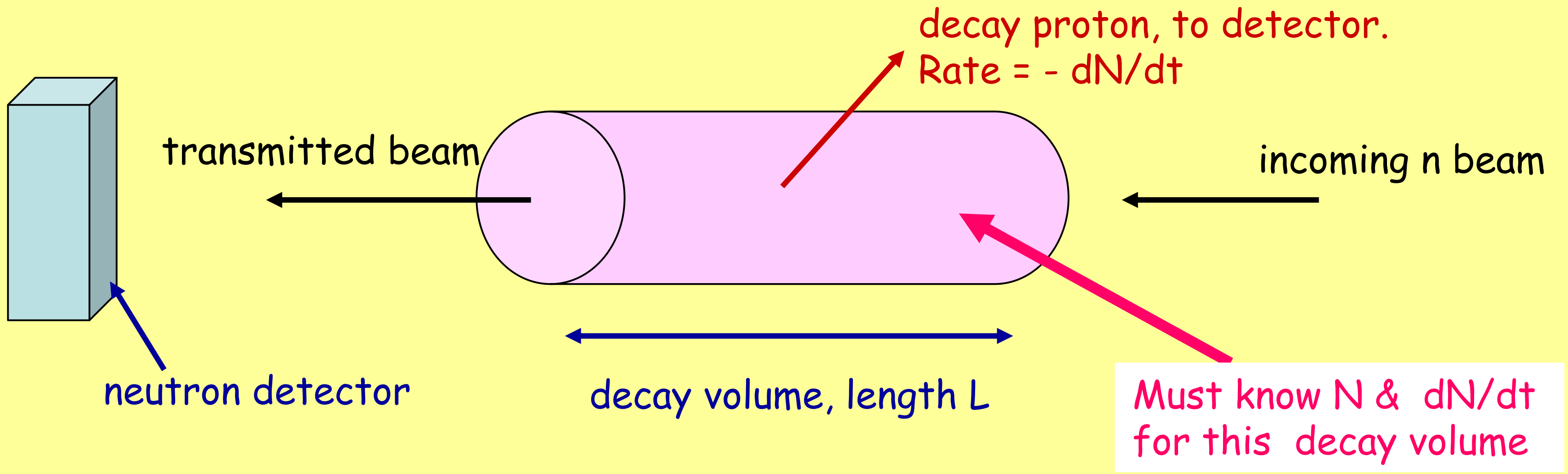
A measurement of the neutron lifetime τ_n performed by the absolute counting of in-beam neutrons and their decay protons has been completed. Protons confined in a quasi-Penning trap were accelerated onto a silicon detector held at a high potential and counted with nearly unit efficiency. The neutrons were counted by a device with an efficiency inversely proportional to neutron velocity, which cancels the dwell time of the neutron beam in the trap. The result is $\tau_n = (886.3 \pm 1.2[\text{stat}] \pm 3.2[\text{sys}])$ s, which is the most precise measurement of the lifetime using an in-beam method. The systematic uncertainty is dominated by neutron counting, in particular, the mass of the deposit and the $^{6}\mathrm{Li}(n,t)$ cross section. The measurement technique and apparatus, data analysis, and investigation of systematic uncertainties are discussed in detail.

DOI: 10.1103/PhysRevC.71.055502 PACS number(s): 21.10.Tg, 13.30.Ce, 23.40.−s, 26.35.+c

Outline of the method: $n \rightarrow p + e^- + \bar{\nu}_e$

decay rate: $$\frac{dN}{dt} = -\frac{N}{\tau}$$

measure rate by counting decay protons in a given time interval (dN/dt) and normalizing to the neutron beam flux (N)



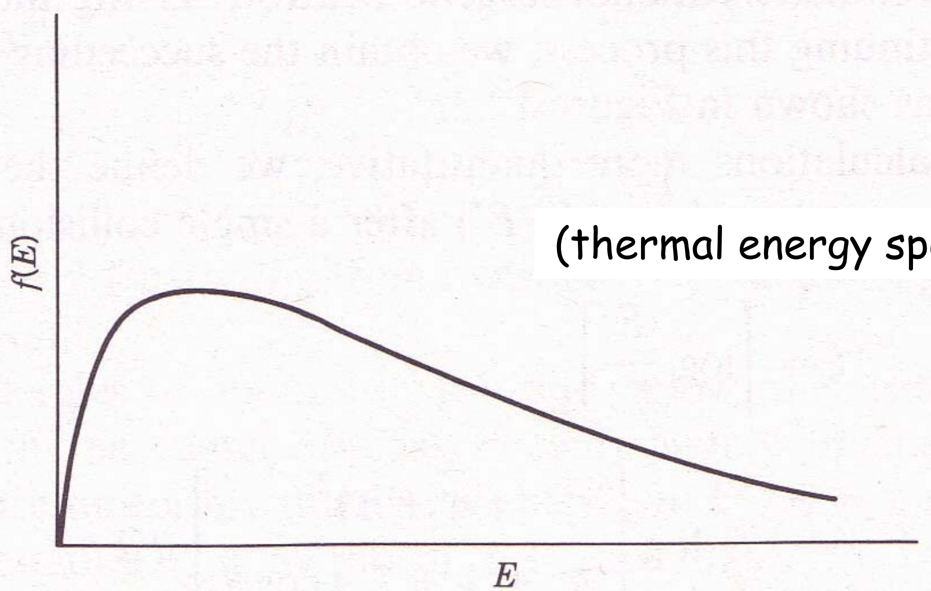
Ideally done with “cold neutrons”, e.g. from a reactor, moderated in liquid hydrogen...

Issues: 1. precise decay volume ? 2. proton detection ? 3. beam normalization ? ...

Neutron beam distribution – definitely **not** monoenergetic:

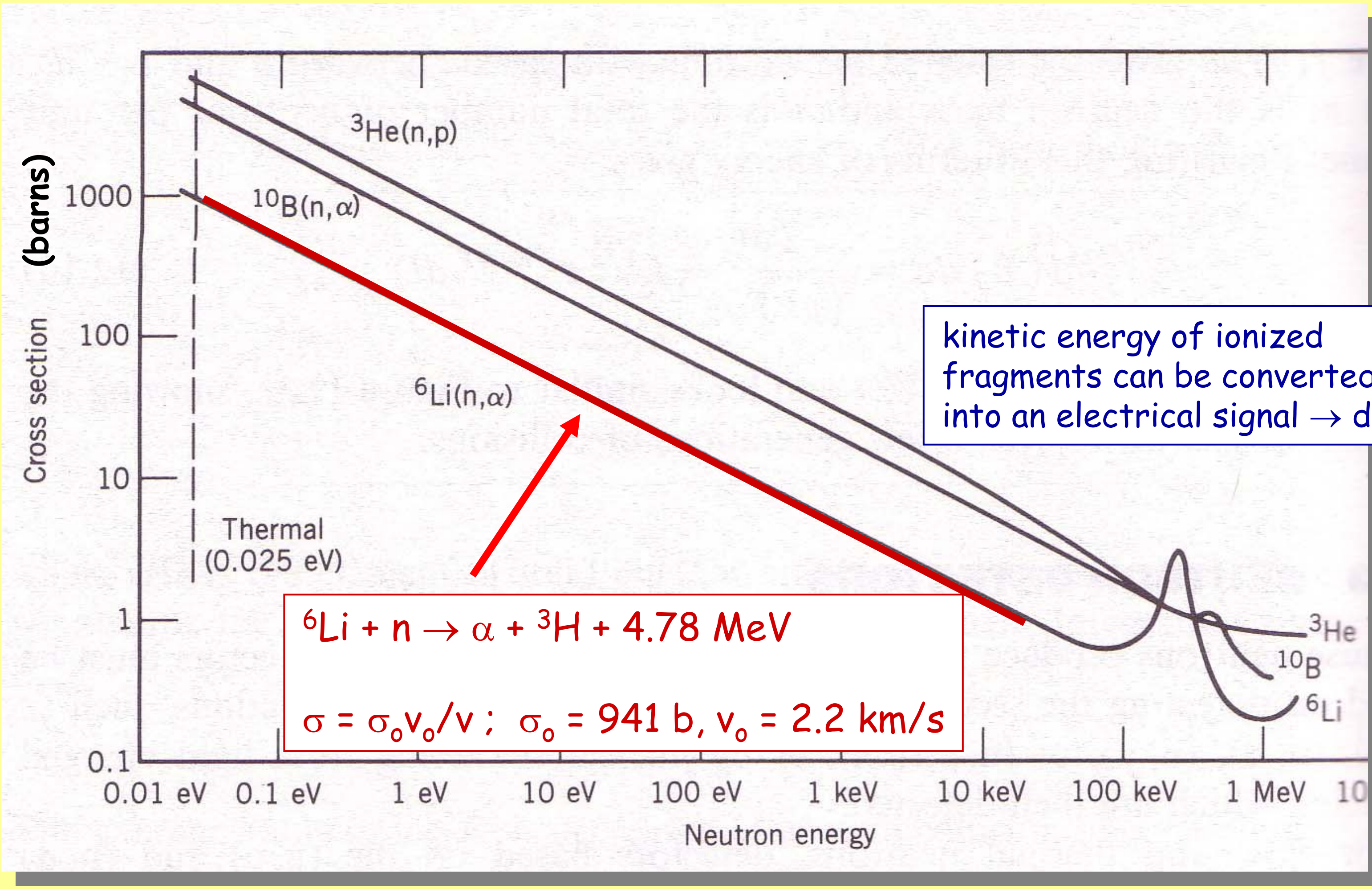
- ~ MeV neutrons from a reactor are "moderated" by scattering in a large tank of water ("thermal") or liquid hydrogen ("cold")
- after many scatterings, they come to thermal equilibrium with the moderator and are extracted down a beamline to the experiment
- velocity distribution is "Maxwellian": energies in the meV range (kT = 26 meV @ 293K)
- beam intensity is constant in time but contains a distribution of velocities!

$$f(v)\,dv = 4\pi n\left(\frac{m}{2\pi kT}\right)^{3/2} v^2\, e^{-mv^2/2kT}\,dv$$



(thermal energy spectrum of the beam)

- several light nuclei have **enormous** neutron capture cross sections at low energy:
  (recall, cross sectional area of a nucleus, e.g. ^{6}Li is about 0.2 barns, lecture 4)
- key feature: cross sections scale as 1/velocity at low energy



$^6\text{Li} + n \rightarrow \alpha + {}^3\text{H} + 4.78$ MeV

$\sigma = \sigma_o v_o / v$; $\sigma_o = 941$ b, $v_o = 2.2$ km/s

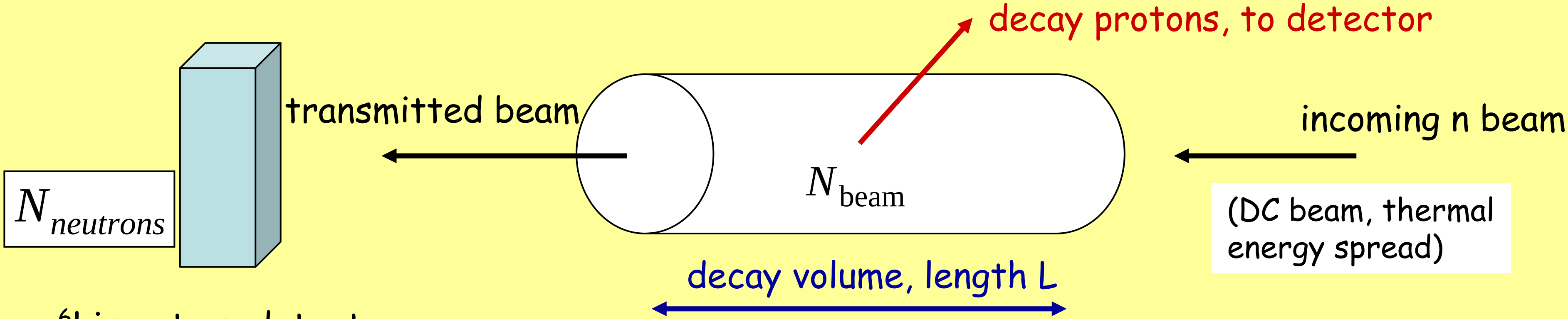
kinetic energy of ionized fragments can be converted into an electrical signal → detector

Decays and transmitted detector counts accumulated for **time T**:

$$\tau = \frac{N_{beam}}{-dN_{beam}/dt}$$

decay rate is small and approx. constant; $dN \ll N$

$$-\frac{dN_{\mathrm{beam}}}{dt} = \frac{N_{protons}}{T}$$



^{6}Li neutron detector

detection probability:

$$P = G\,\sigma = G\,\frac{\sigma_o \mathrm{v}_o}{\mathrm{v}}$$

(G = geometry factor – measure by calibrating the detector!)

Neutron detector signal:

$$N_{beam} = N_n / P = \frac{N_n\,\mathrm{v}}{\mathrm{G}\,\sigma_\mathrm{o}\mathrm{v}_\mathrm{o}} = (const) \times N_n \times \frac{L}{T}$$

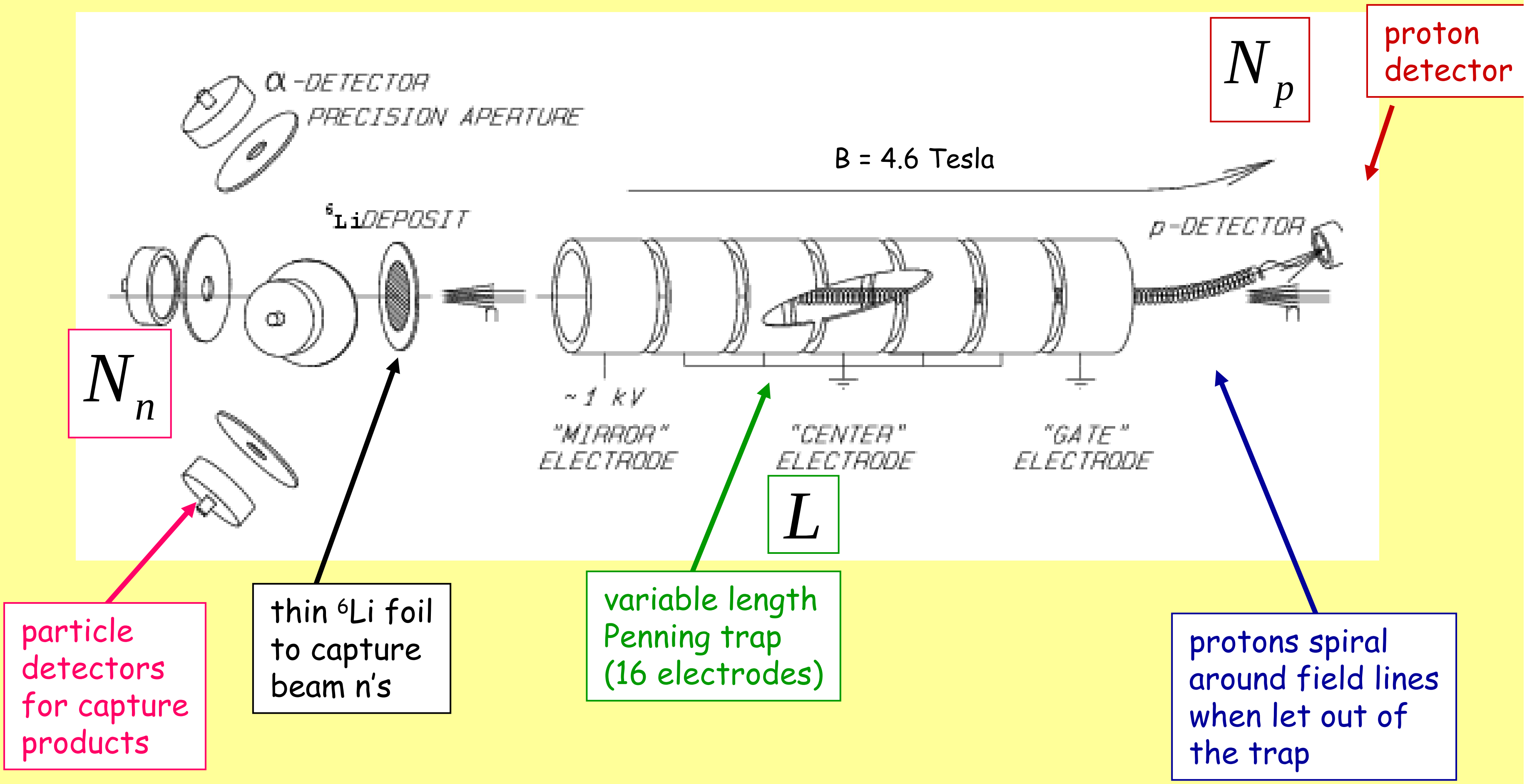
Neutron lifetime:

$$\tau = \frac{N_{beam}}{-dN_{beam}/dt} = (const) \times \frac{N_n}{N_p} \times L$$

Experimental details (all in vacuum, at NIST reactor, Gaithersburg MD, USA):

- use Penning trap to confine decay protons
- let them out of the trap after accumulation interval T
- measure the ratio N_n/N_p as a function of trap length L $\rightarrow$ slope gives τ

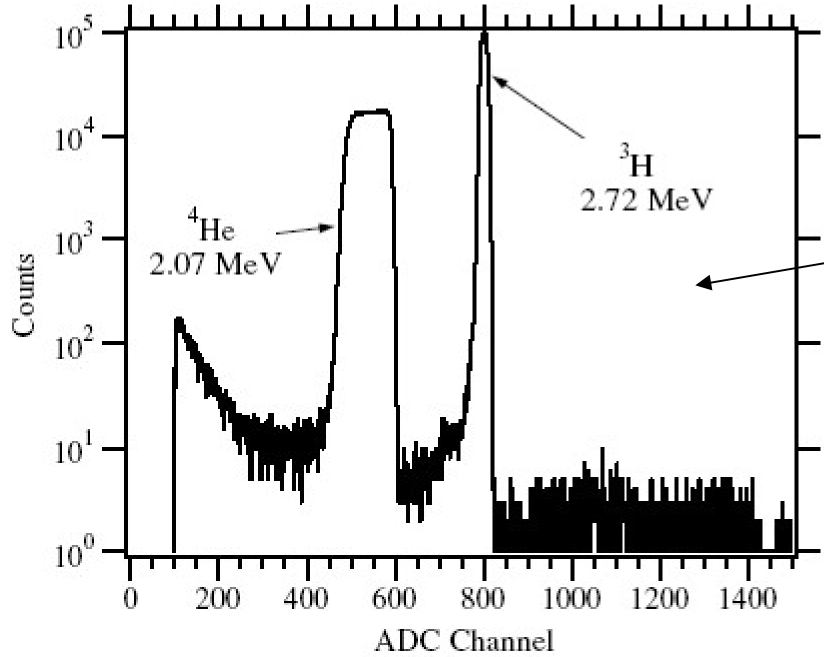
$$\tau \sim \frac{N_n}{N_p} \times L$$



Apparatus at NIST

Penning trap close up:

http://physics.nist.gov/Divisions/Div846/Gp3/FunPhys/lifetime.html



pulse height spectrum in neutron monitor
$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}He + 4.79\ MeV$

Challenge for proton detection:

Max K.E. of proton is 751 eV → too low to penetrate even a thin detector and measure the energy accurately.

Solution: accelerate the protons in an electric field!

Residual correction to lifetime for protons backscattering from the detector surface is a few seconds in 885 sec.

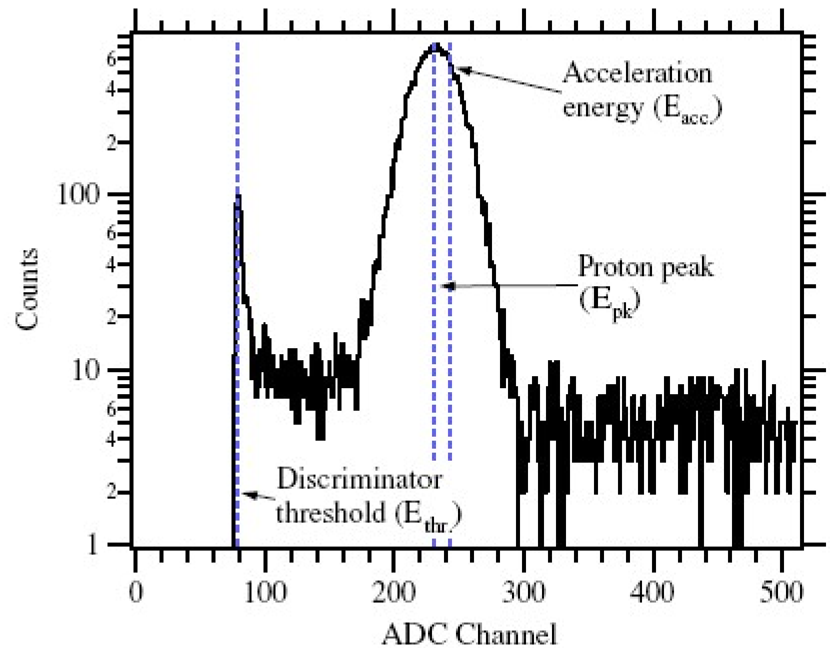
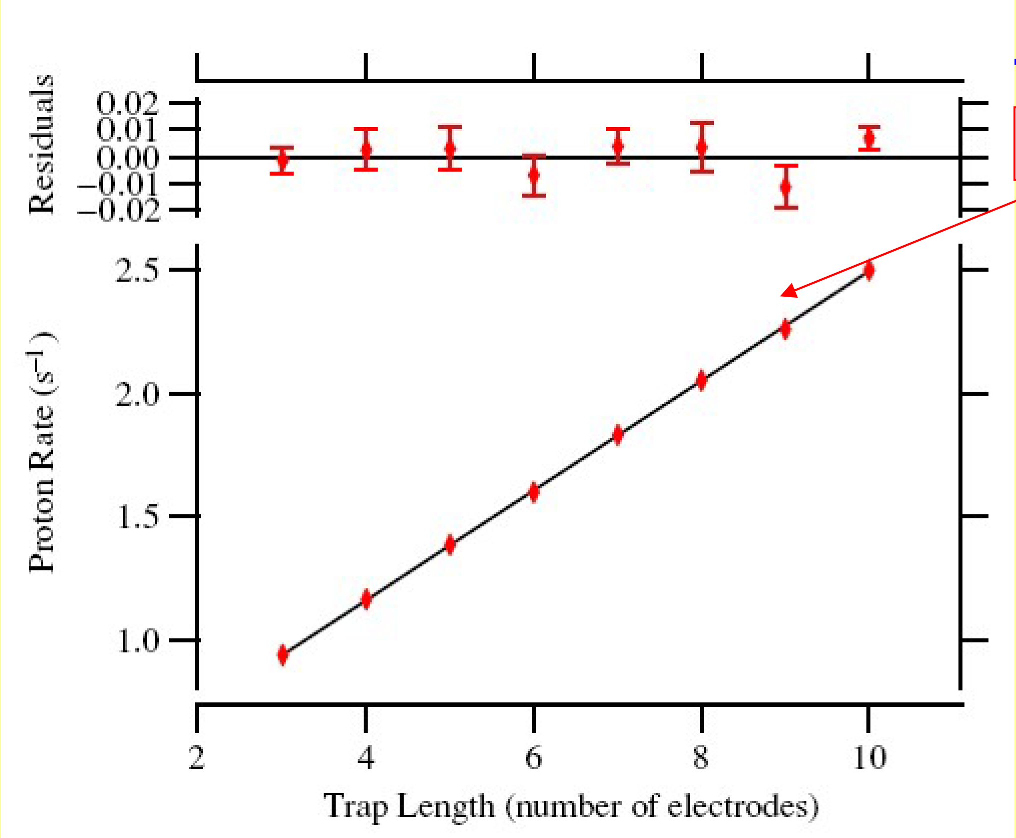


FIG. 18. (Color online) A proton pulse-height spectrum for a typical run. The acceleration energy of the protons was 32.5 keV, and the detector was a surface barrier detector with 40 $\mu g/cm^2$ of gold. The energy loss E_{loss} is the difference between the acceleration energy and the energy of the peak, or 1.64 keV.

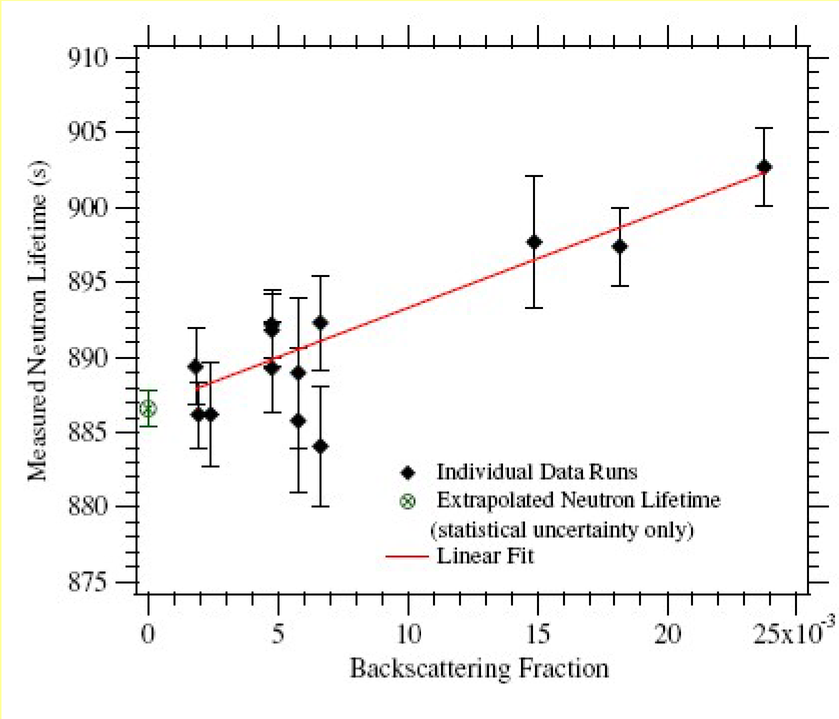
Measurements:

$$\tau \sim \frac{N_n}{N_p} \times L$$

Proton rate versus L



Final correction for fraction of protons missed due to backscattering from the detector



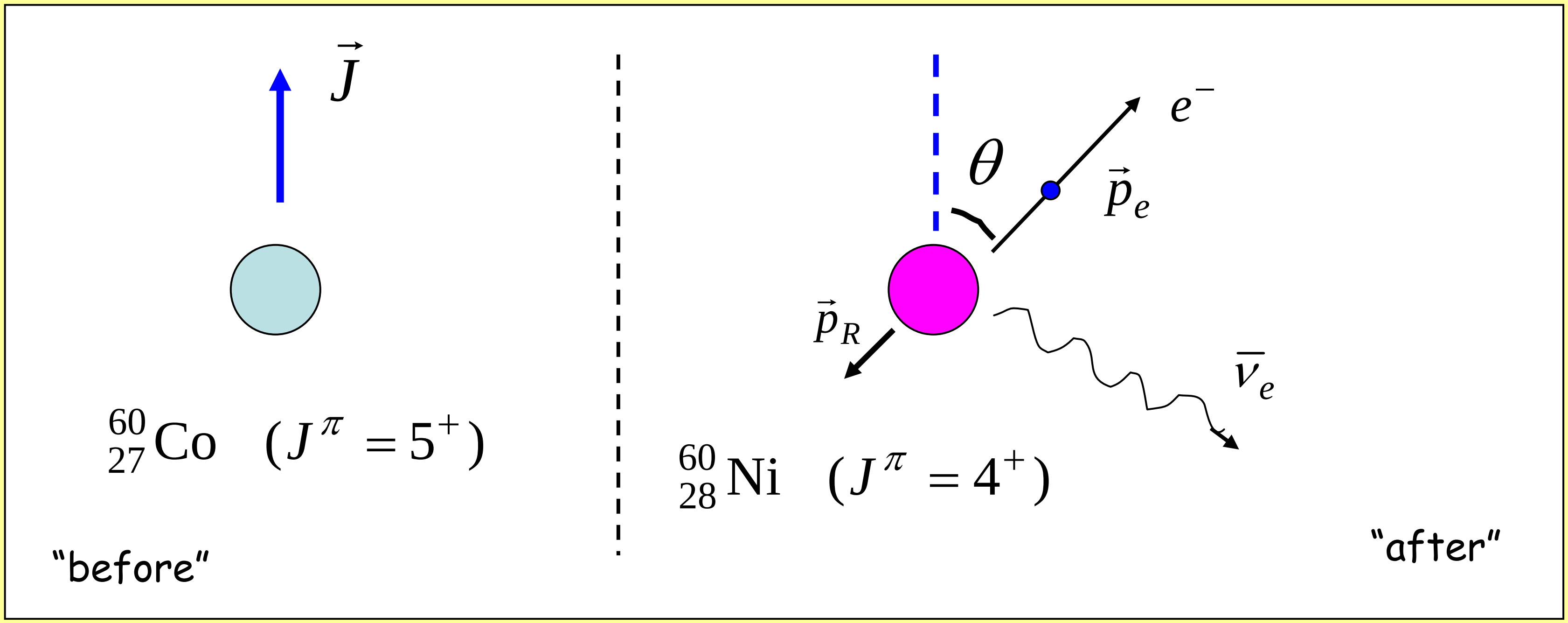
RESULT:

The result of the lifetime measurement is $\tau_n = (886.3 \pm 1.2[\text{stat}] \pm 3.2[\text{sys}])$ s, which is the most precise measurement of the lifetime using an in-beam method. This result is in good agreement with the current world average [10]. The systematic uncertainty is dominated by neutron counting, in particular the areal density of the ^{6}LiF deposit and the ^{6}Li(n,t) cross section.

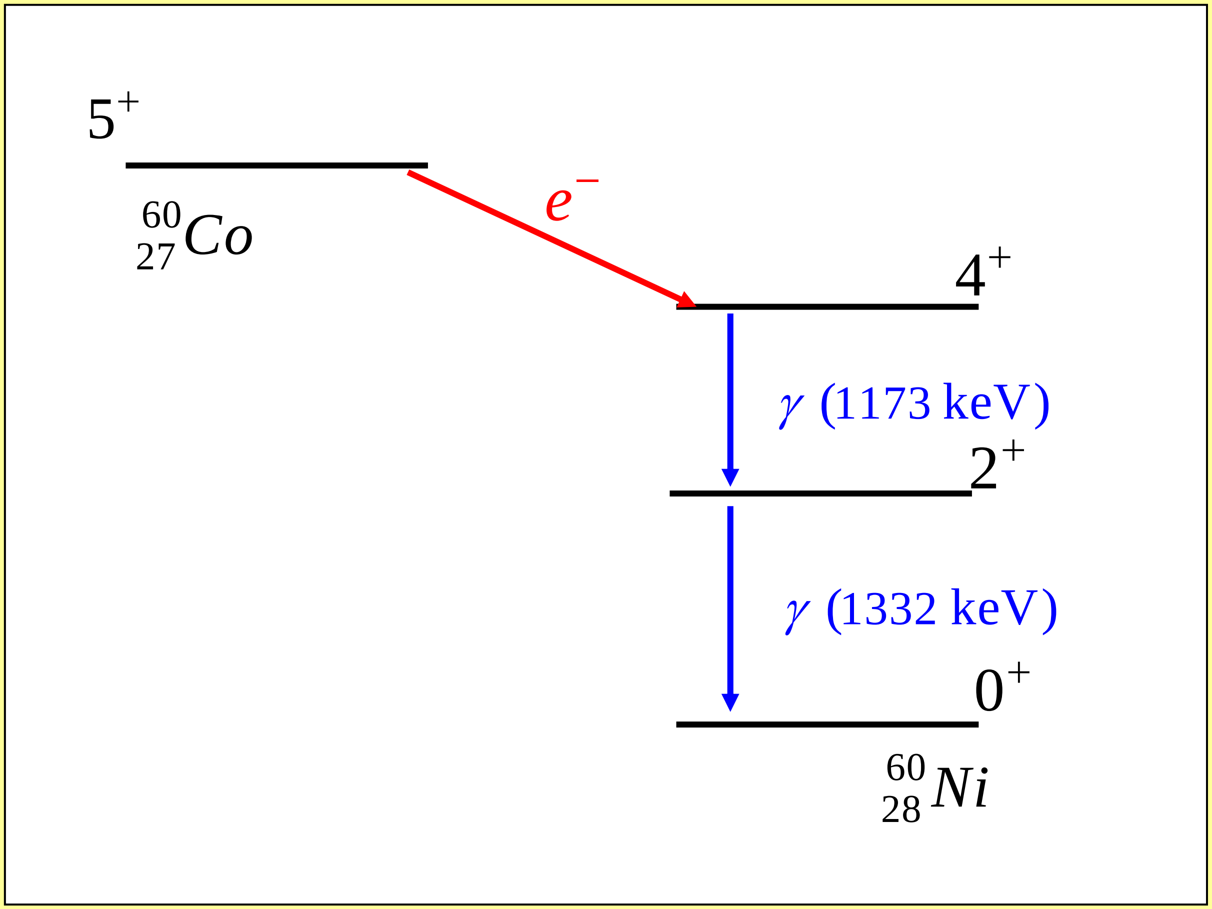
Famous experiment carried out by C.S. Wu (1957) at the suggestion of Lee & Yang (1956, Nobel Prize 1957) demonstrated that the weak interaction violates parity

$$^{60}_{27}\mathrm{Co} \to {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e$$

Key observation: when cobalt nuclei were polarized in a magnetic field at low temperature, electrons were emitted preferentially in a direction **opposite** to the nuclear spin…



60 Co Decay Scheme:



- two famous gamma rays, 1173 and 1332 keV (cobalt radiation therapy!)
- high spin of ^{60}Co plus magnetic property means it can be polarized in a B field
- angular distribution of gamma rays reveals polarization of the ^{60}Co "parent" nucleus

Figures from C.S. Wu et al., Phys. Rev. 105, p. 1413 (1957)

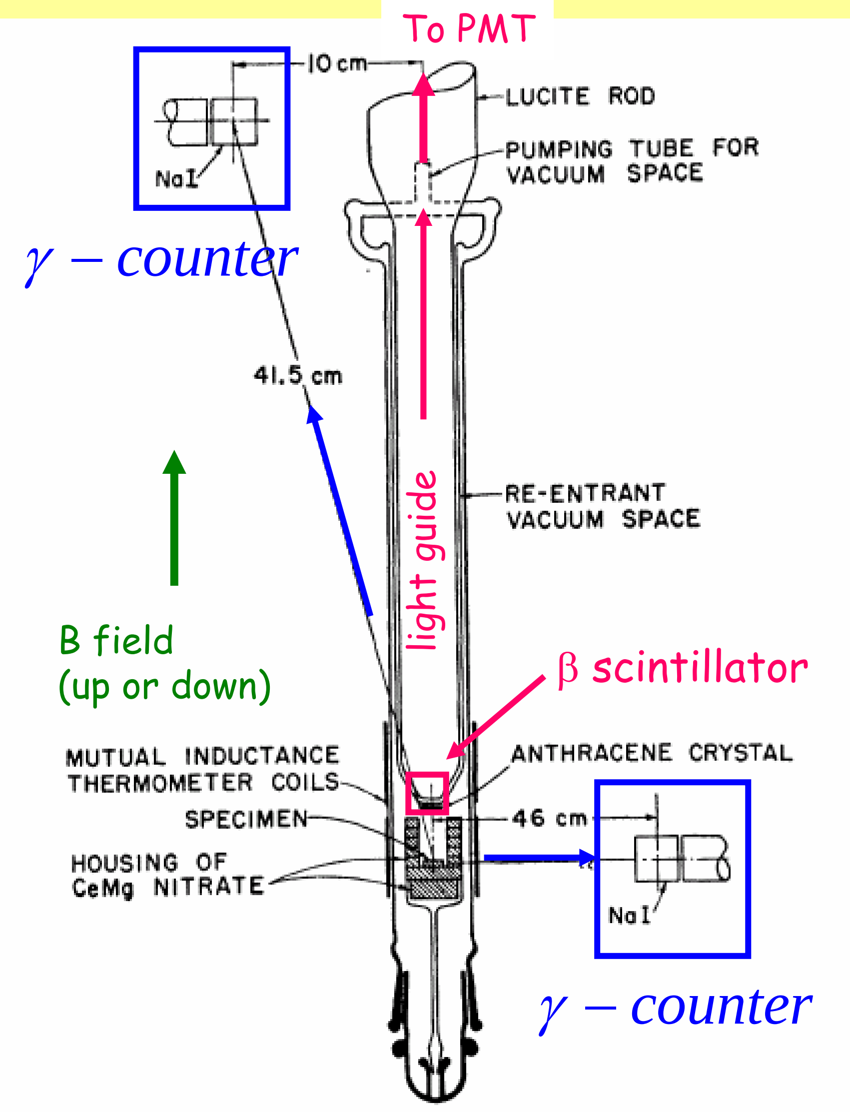


FIG. 1. Schematic drawing of the lower part of the cryostat.

γ anisotropy measures nuclear polarization

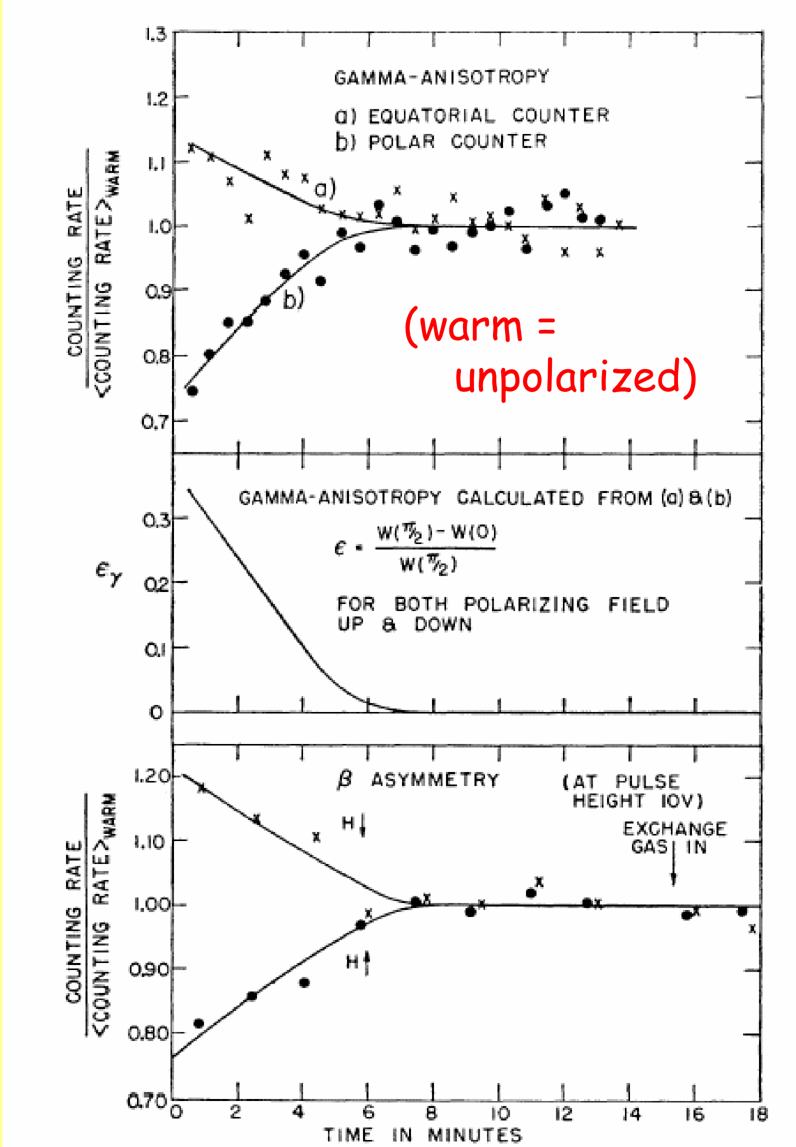
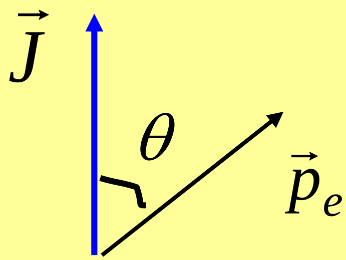


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

A pseudoscalar observable:



electron emission angle: $\theta \sim \left\langle \vec{J} \bullet \vec{p}_e \right\rangle$

Under a parity transformation: $\vec{r} \Rightarrow -\vec{r}$

Angular momentum: $$\vec{J} \sim \vec{r} \times \frac{d\,\vec{r}}{dt} \Rightarrow (-\vec{r}) \times \left(\frac{-d\,\vec{r}}{dt} \right) \sim \vec{J}$$

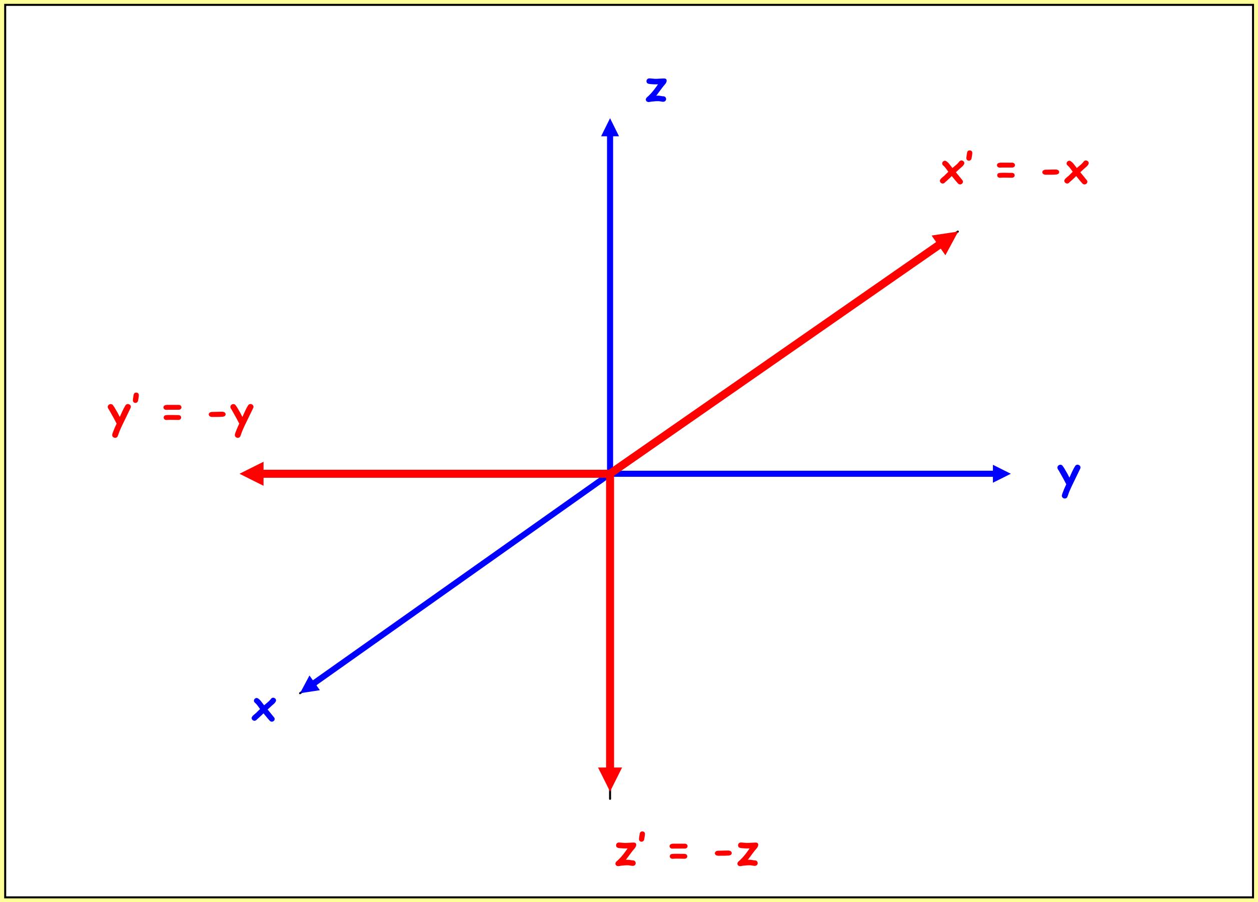
Linear momentum: $$\vec{p} \sim \frac{d\,\vec{r}}{dt} \Rightarrow \frac{-d\,\vec{r}}{dt} \sim -\vec{p}$$

$$\boxed{\left\langle \vec{J} \bullet \vec{p} \right\rangle \Rightarrow -\left\langle \vec{J} \bullet \vec{p} \right\rangle}$$

Observer using a parity-reversed coordinate system deduces the opposite correlation of e- and J… but this is “crazy”…. ????

Consider what a parity transformation does to a coordinate system: $\vec{r} \Rightarrow -\vec{r}$

"Normal" RIGHT-handed Cartesian system: $\hat{i} \times \hat{j} = \hat{k}$



Reverse of coordinate axes: x' = -x, etc. → the system is LEFT-handed: $\hat{i}' \times \hat{j}' = -\hat{k}'$

Laws of physics should be independent of coordinate system! In particular, a right-handed and left-handed choice of Cartesian coordinates should be completely arbitrary. (We should get the same answer both ways.)

(True for gravity, strong, and electromagnetic interactions)

This is **not true** for the weak interaction:

$\left\langle \vec{J} \bullet \vec{p} \right\rangle$ has the **opposite sign** in LH and RH systems

$\rightarrow$ by demonstrating a preferred correlation $-\left\langle \vec{J} \bullet \vec{p} \right\rangle$, beta-decay "prefers" a LH coordinate system $\rightarrow$ symmetry is broken!

In fact, the electron and antineutrino themselves show a similar correlation:

define **"helicity"** h:

$$h = \frac{\langle \vec{s}.\vec{p} \rangle}{s\ p}, \quad -1 \le h \le +1$$

for a particle with spin s, and momentum p

Electrons emitted in β-decay have h = -v/c "left handed"
(positrons " " h = +v/c "right handed")

Neutrinos have h = -1 (LH) and antineutrinos have h = +1 (RH) -- this is the only perceptible difference between them!!!!!